Low-energy RHIC electron Cooler (LEReC)

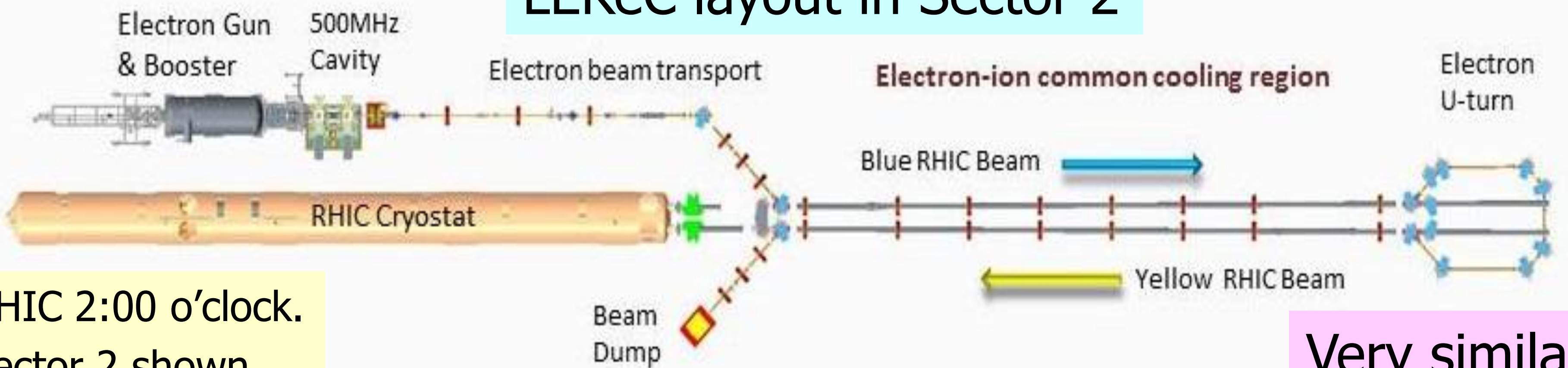
timing/controls

October 31, 2013

Timing topics

- **Putting “train” of electron bunches on single ion bunch**
- **Cooling ions in both RHIC rings with the same electron beam**
- **Locking electron bunch pattern on ion bunch and requirements**

LEReC layout in Sector 2



RHIC 2:00 o'clock.
Sector 2 shown.

Very similar to CeC PoP accelerator

- **84.5 MHz SRF gun with maximum energy of 2.5 MV.**
- **2.5 MV booster 84.5 MHz SRF cavity in the same cryostat.**
- **507 MHz energy correction warm cavity (6^{th} harmonic).**
- **Electron beam transport.**
- **Cooling section in Blue RHIC ring – 20 m long. Short (10cm) correction solenoids (200G) located every 2m. U-turn between cooling section in Blue and Yellow RHIC rings.**
- **Cooling section in Yellow Ring.**
- **Dump for the electron beam.**

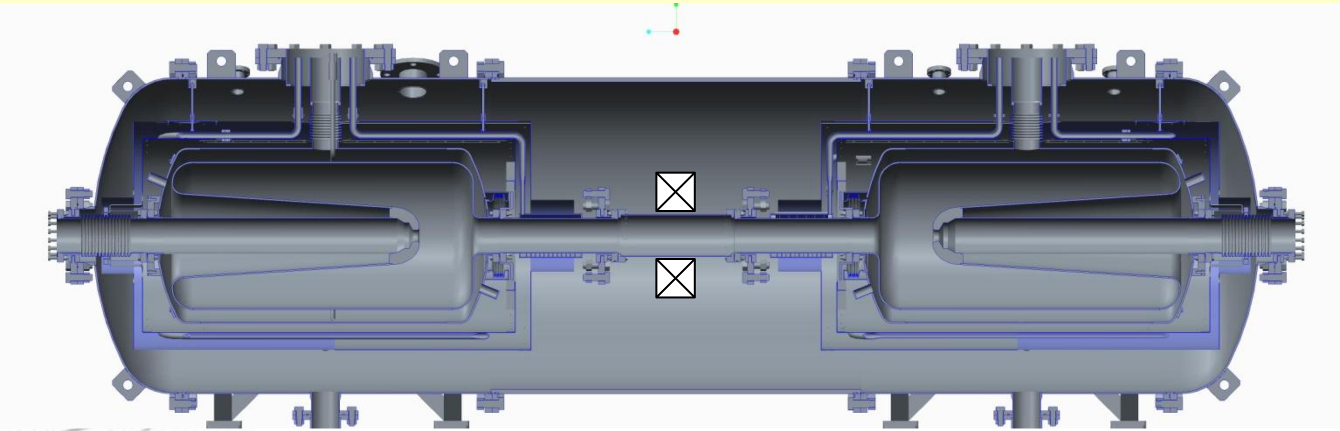
SRF gun design considerations

- The SRF gun design will be similar to the 112 MHz SRF gun built by Niowave for the Coherent Electron Cooling (CeC) experiment at BNL (under construction) with the following major differences:
    1) The gun cavity shape will be optimized to improve surface fields and reduce wall losses;
    2) The gun will be equipped with two high-power fundamental RF power couplers;
    3) There will be a frequency tuner of an improved design.

112 MHz SRF gun (Niowave Inc.) installed in RHIC tunnel for the CEC PoP experiment at IP2.

LEReC SRF accelerator

- The electron accelerator (a short linac) will consist of a two-cavity superconducting RF (SRF) cryomodule producing beam with energy up to 5 MeV and normal conducting cavity for energy spread correction.
- The cryomodule will house:
  - A photoemission SRF gun of a quarter wave resonator (QWR) type, operating at 84.5 MHz;
  - A 84.5 MHz QWR SRF booster cavity;
  - There will be a superconducting solenoid (with magnetic field up to 1 kG) between two SRF cavities.
- 507 MHz normal conducting cavity will correct energy spread due to RF curvature of the SRF cavities.



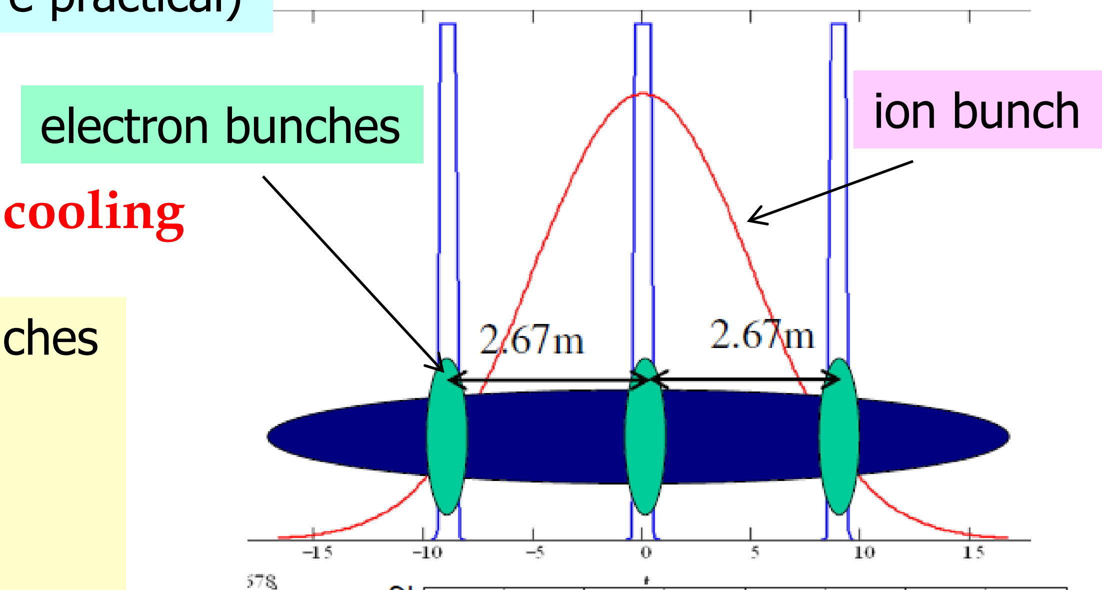
designed
in collaboration
with ANL

Bunched beam electron cooling

A natural way for high-energy cooling
(when RF acceleration becomes more practical)

LEReC:

- **First bunched beam electron cooling**

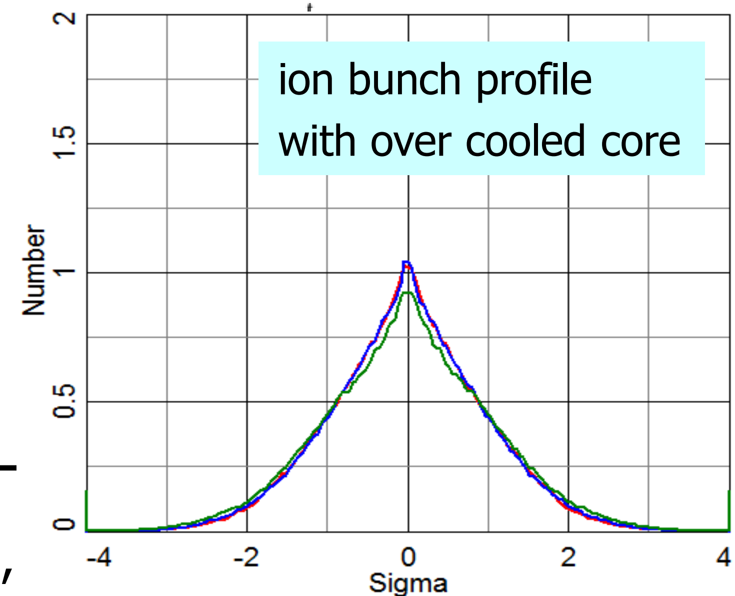


1) Putting a “train” of electron bunches on a single ion bunch.

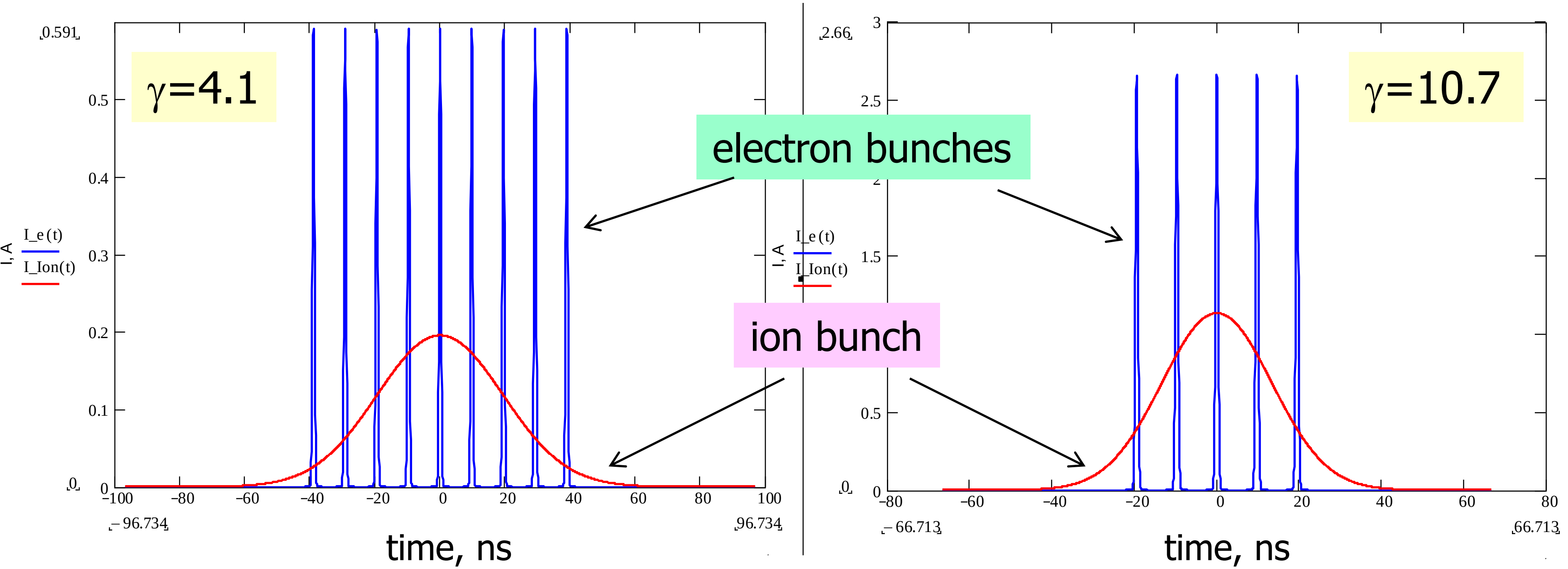
2) Possibly “painting” through ion bunch length.

- **First electron cooling in a collider**

Requires careful control of ion beam distribution under cooling to avoid over cooling (shown in the plot) of beam core.



Using “trains” of electron bunches for cooling

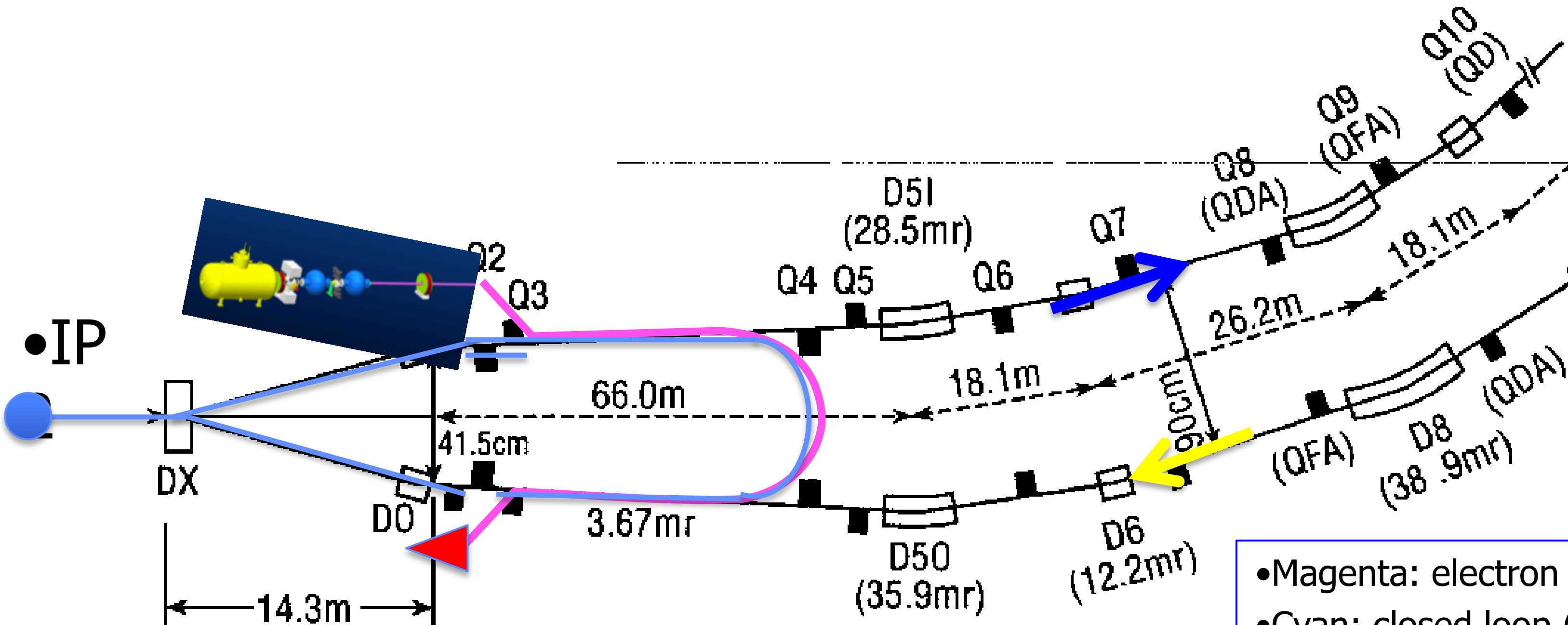


γ=4.1, Q=0.45 nC/bunch , length=0.75 ns,
I_peak=0.6A, (bunches 12 ns apart)

γ=10.7, Q=2nC/bunch , length=0.75 ns,
I_peak=2.5A, (bunches 12 ns apart)

- **Electron cooling will be provided with a train of electron bunches placed on a single ion bunch.**
- **For very long ion bunches (for 4.5 MHz RF) at lowest energies in RHIC we can place up to 9 electrons bunches on a single ion bunch.**
- **For higher energies we can place 5 electron bunches on a single ion bunch.**

•Same electron beam is used for cooling both ion beams

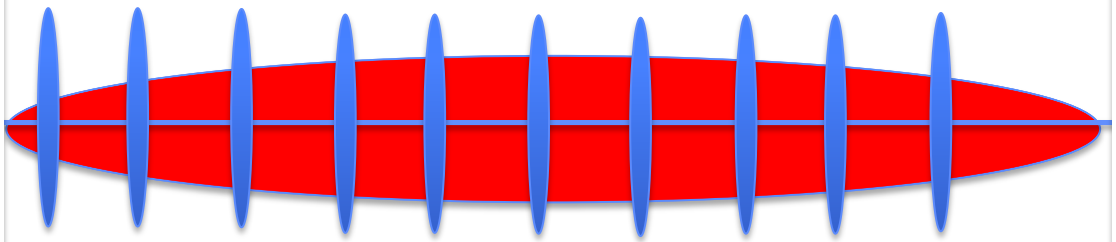


- Magenta: electron trajectory
- Cyan: closed loop (marker)
- Black: blue and yellow RHIC rings

•Closed loop from IP through RHIC rings, e-bunch turn around and back to the IP (cyan color) has to be integer number of RHIC bunches distance (63.9m corresponds to 60 bunches in each RHIC ring L_{RHIC}=3834 m)

Multiple of 32m for 120 bunches (9MHz RHIC RF)

Timing and synchronization (by Vladimir Litvinenko)



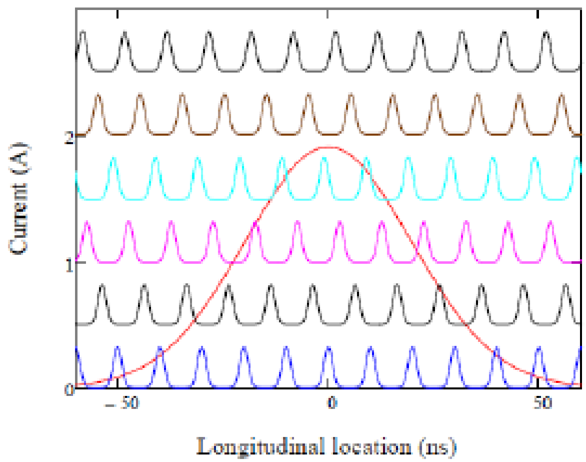
- **Since SRF frequency is not widely tunable, in general we are operating with electron bunches sliding through the hadron beam**
- **Possibility of emittance growth from slipping bunches (summary – next few slides)**
- **Solution is to keep fixed e-beam pattern over-lapping the hadron bunch**

Effects of electrons on hadrons

- In the electron cooling section, ions get focused by the electrons. The focusing strength from electrons can vary from turn to turn due to bunch charge jitters, arriving time jitters and electron bunch slipping with respect to ion bunch.
- The time-varying focusing can change an ion’s Courant-Snyder invariant (action) as calculated from the time-independent linear lattice, which in combination of amplitude detuning, can lead to emittance growth of the ion beam.

Gang Wang

Focusing Strength from Slipping Electron Beam



$$I_e(t)=\frac{Q_e}{\sqrt{2\pi}\sigma_e}\sum_{n=-\infty}^{\infty}\exp\left[-\frac{(t-n\cdot\Delta T_e)^2}{2\sigma_e^2}\right]$$

$$\alpha=\frac{2r_0\beta_{avg}}{\gamma^3\beta^2a_e^2}\frac{L_{cool}}{\beta ce}$$

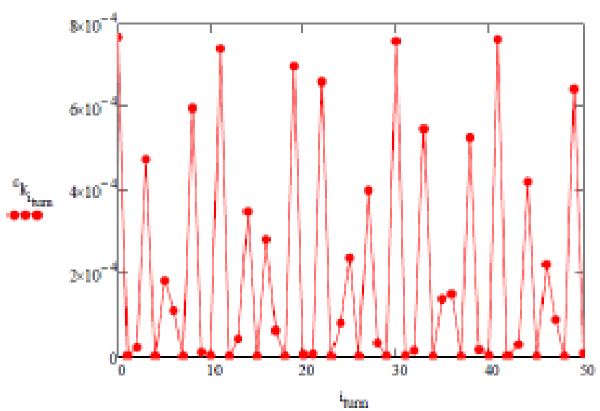
$$\varepsilon_M=\alpha\cdot I_e(M,0)$$

$$\approx 4\pi\cdot\Delta\nu_{peak}\cdot\exp\left\{-\frac{\left[M\cdot\nu_e-Round(M\cdot\nu_e)\right]^2\Delta T_e^2}{2\sigma_e^2}\right\}\quad \text{for } \Delta T_e>>\sigma_e$$

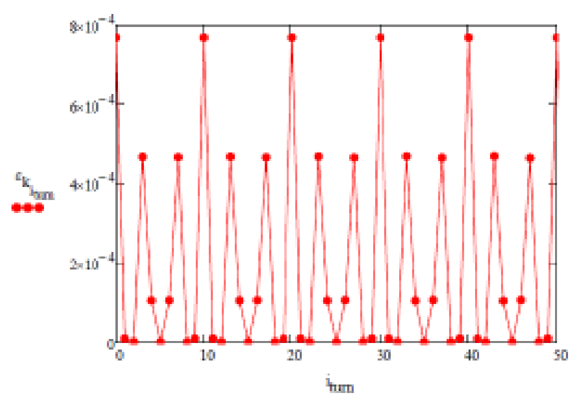
$$\nu_e=\mathrm{mod}\left(\frac{f_{e,rep}}{f_{i,rev}},1\right)$$

$$\Delta\nu_{peak}=\frac{N_e}{2\pi\sqrt{2\pi}\sigma_e}\frac{r_0\beta_{avg}}{\gamma^3\beta^3a_e^2}\frac{L_{cool}}{c}$$

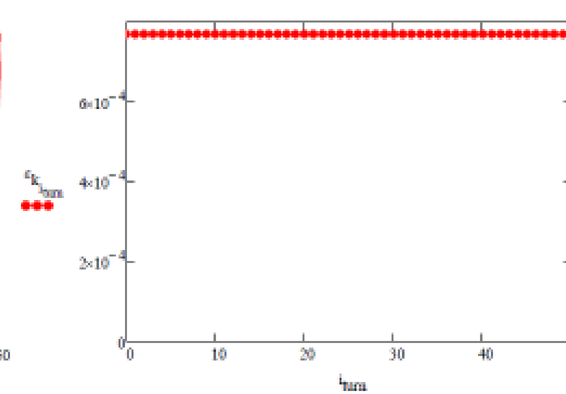
$\nu_e=0.36613$



$\nu_e=0.3$



$\nu_e=0$

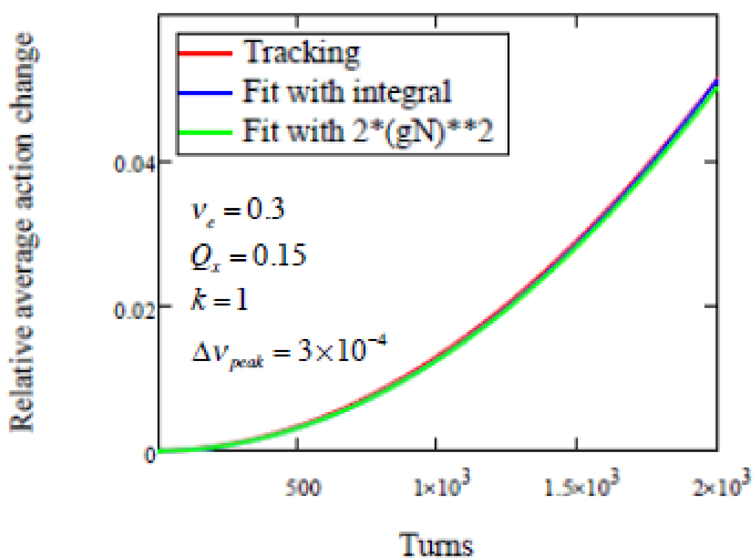


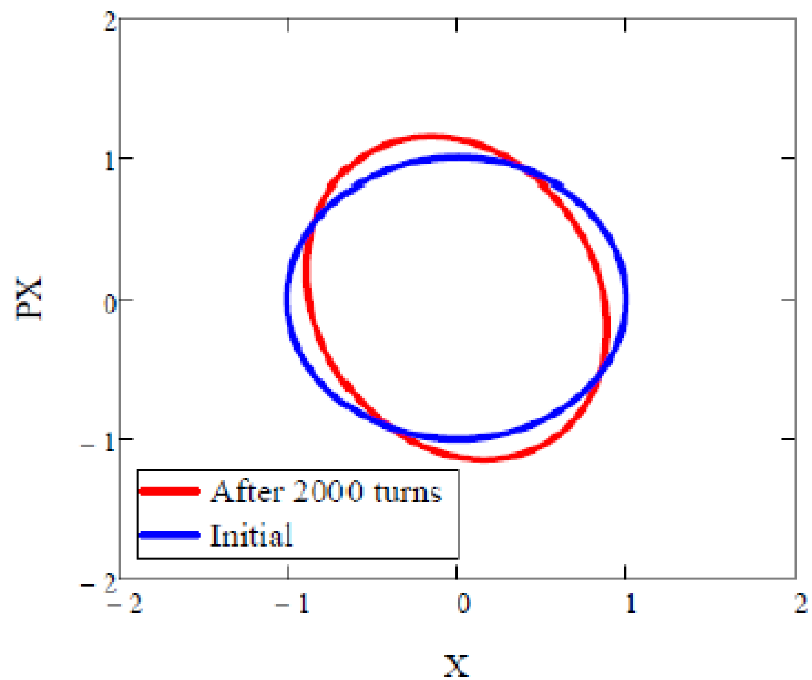
1D Tracking

Example of resonant growth (G. Wang)

$$P = \frac{p}{\sqrt{Q}} = \sqrt{2J}\cos\psi \qquad X = x\sqrt{Q} = \sqrt{2J}\sin\psi$$

$$\begin{cases} X_n(k+1) = \cos(2\pi Q_x)X_n(k) + \sin(2\pi Q_x)P_n(k) \\ P_n(k+1) = \cos(2\pi Q_x)P_n(k) - \sin(2\pi Q_x)X_n(k) + \varepsilon_k X_n(k+1) \end{cases}$$

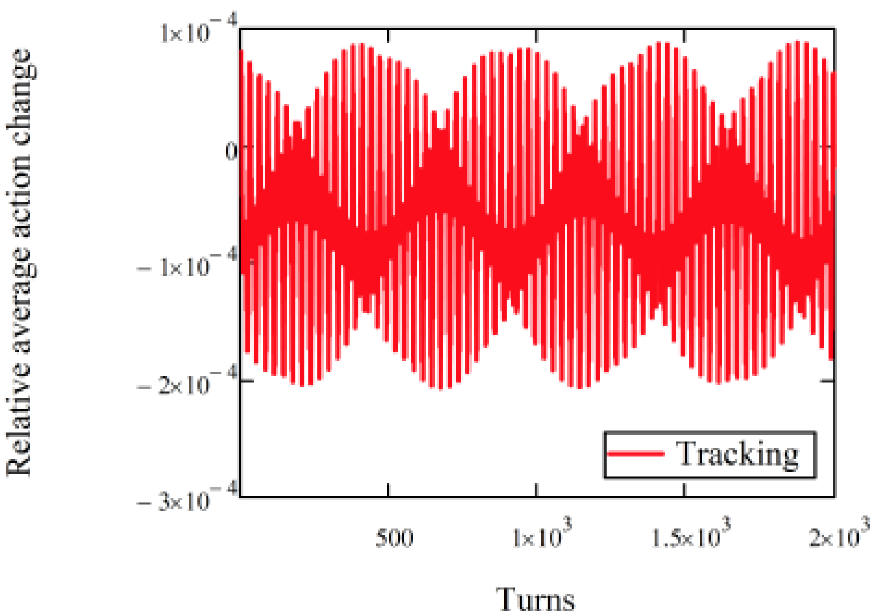


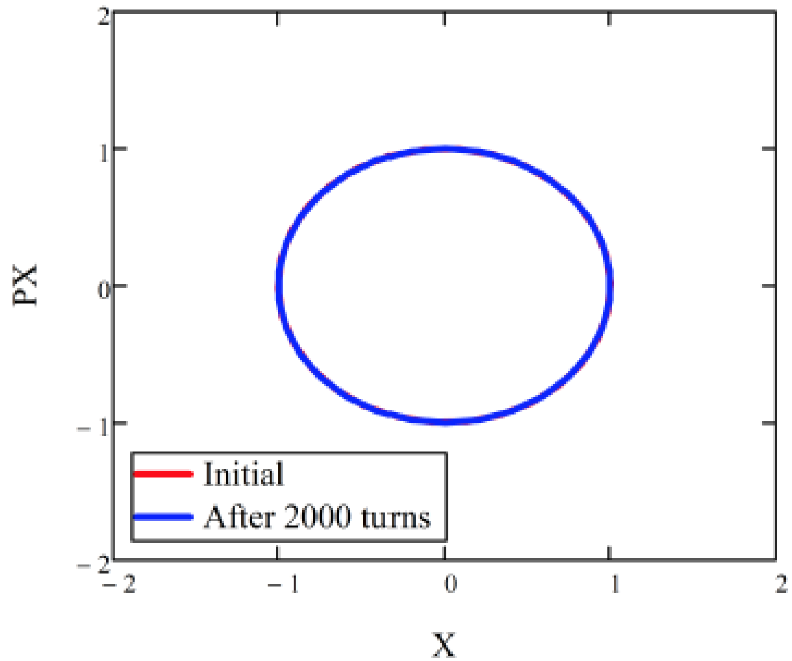


Non-resonant Driving From Slipping Electron Bunch (1D Tracking)

$$\nu_e = 0.36613$$
$$Q_x = 0.15$$
$$\Delta \nu_{peak} = 3\times 10^{-4}$$

The average action oscillates but no growth is observed.





Gang Wang

Summary
of effects of electrons on hadron beam

- Slipping electron bunch can be considered as a bunch of rf quadruples, which can drive ion beam resonantly and lead to its emittance growth if the resonant condition, $(2\tilde{Q})_{frac.} \pm k\nu_e = K$, is satisfied. We plan to avoid the resonant driving by choosing $\nu_e = 0$
- Peak current jitters of the electron bunches lead to random focusing variations to the ions in the cooling section, which can cause ion beam emittance growth. The rms current variation should be under 7% to keep the ion emittance growth time longer than 1000 seconds.
- Arriving time jitters of the electron bunch will also cause focusing variations seen by ions and hence ion beam emittance growth. The rms arriving time variation should be under 120 ps to keep the ion emittance growth time longer than 1000 seconds.

Electron beam pattern on ion beam (V. Litvinenko)

- **Electron beam has following pattern:**

$$I_e(t)=\sum_{M=-\infty}^{\infty} I_b(t+M\tau_o);\quad \tau_o=\frac{1}{f_{SRF}}$$

- **Hadron sees on Nth turn**

$$I_x(t)=\int\delta(t-NT)\sum_{M=-\infty}^{\infty} I_b(t+M\tau_o)=\sum_{M=-\infty}^{\infty} I_b(M\tau_o-NT);\quad T=\frac{c\cdot\beta}{C}$$

- **Pattern repeats itself if**

$$T=M\tau_o \;\Leftrightarrow\; f_{rev}=f_o\frac{\beta_o}{\beta}=\frac{f_{SRF}}{M}$$

Fixed pattern

Example is given for f_srf=112 MHz

Present baseline: f_srf=84.47 MHz

$$T = M t_o \iff f_{rev} = f_o \frac{\beta_o}{\beta} = \frac{f_{SRF}}{M}$$

- **In our case let's select energy of 10 GeV/u:**

$$at\ \gamma_o = 1/\sqrt{1-\beta_o^2} : h = \frac{f_{SRF}}{f_o} = 12*120 = 1440$$

- **Lets introduce fixed pattern conditions**

$$M = h + m$$

$$\boxed{\beta_m = \beta_o \times \frac{h+m}{h}}$$

RHIC	**Circumference**	**3833.845**	**m**
Central energy	10	GeV	
γo	10.65788673		
βo	0.995588495		
fo	7.85428E+04	Hz	
ho	1440		

Fixed pattern condition

m	γ	E, GeV/n
6	43.58672065	40.90
5	22.8916853	21.48
4	17.43617746	16.36
3	14.63443225	13.73
2	12.85827895	12.06
1	11.60407568	10.89
0	10.65788673	10.00

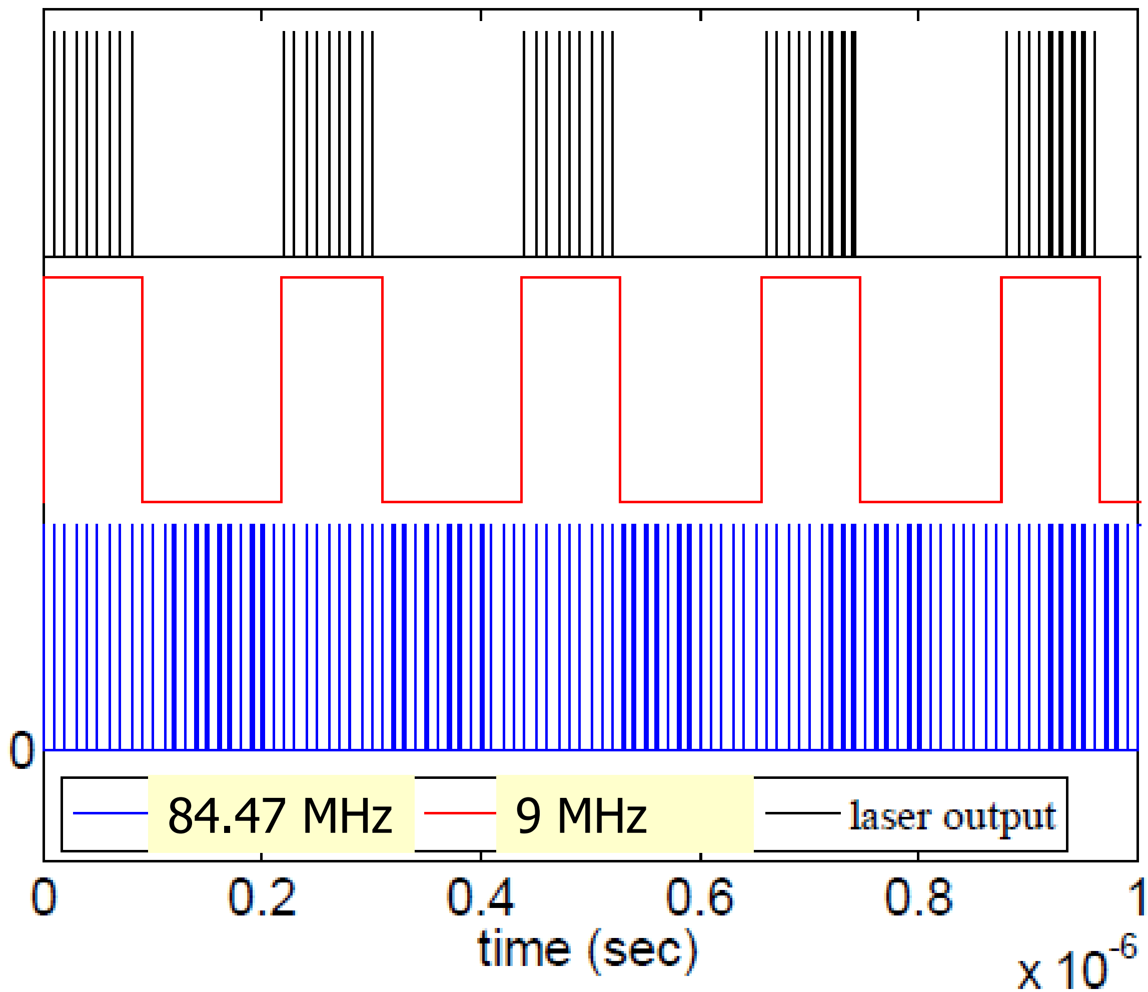
0	10.65788673	10.00
-1	9.911327032	9.30
-2	9.302844534	8.73
-3	8.794550129	8.25
-4	8.361675153	7.85
-5	7.987254135	7.49
-6	7.659224348	7.19
-7	7.368742777	6.91
-8	7.109159308	6.67
-9	6.875363729	6.45
-10	6.663355669	6.25
-11	6.469952771	6.07
-12	6.292587489	5.90
-13	6.12916235	5.75
-14	5.977944802	5.61
-15	5.837489447	5.48
-16	5.706579615	5.35
-17	5.584182841	5.24
-18	5.469416494	5.13
-19	[illegible]	5.03
-20	5.259838323	4.94

-21	5.163795728	4.85
-22	5.072891535	4.76
-23	4.986684428	4.68
-24	4.904784381	4.60
-25	4.826845235	4.53
-26	4.75255856	4.46
-27	4.681648521	4.39
-28	4.613867585	4.33
-29	4.54899289	4.27
-30	4.486823174	4.21
-31	4.427176155	4.15
-32	4.369886289	4.10
-33	4.314802848	4.05
-34	4.261788255	4.00
-35	4.210716646	3.95
-36	4.161472618	3.90
-37	4.113950137	3.86
-38	4.068051583	3.82
-39	4.023686911	3.78
-40	3.98077291	3.74
-41	3.939232554	3.70
-42	3.898994418	3.66
-43	3.85999217	3.62
-44	3.822164111	3.59
-45	3.785452767	3.55
-46	3.749804526	3.52
-47	3.715169309	3.49
-48	3.681500277	3.45
-49	3.648753566	3.42
-50	3.616888049	3.39

....

-75	3.023862494	2.84
-76	3.00598814	2.82
-77	2.988439814	2.80
-78	2.971207811	2.79
-79	2.954282827	2.77
-80	2.937655935	2.76
-81	2.921318569	2.74
-82	2.905262501	2.73
-83	2.889479828	2.71
-84	2.873962954	2.70
-85	2.858704575	2.68
-86	2.843697664	2.67
-87	2.828935459	2.65
-88	2.814411449	2.64
-89	2.800119364	2.63
-90	2.786053161	2.61
-91	2.772207016	2.60
-92	2.758575312	2.59
-93	2.745152632	2.58
-94	2.731933746	2.56
-95	2.718913609	2.55
-96	2.706087345	2.54
-97	2.693450246	2.53
-98	2.680997762	2.52
-99	2.668725494	2.50
-100	2.656629189	2.49

Bunch pattern



Recent changes:

Electrons:

f_srf: 100-> 84.47 MHz

Ions:

f_rf_RHIC: 4.5 -> 9MHz

- Bunch train frequency is locked at 120th harmonic of RHIC revolution frequency (changes with energy).

- Microbunch frequency is Mth harmonic of revolution frequency.

Control/timing requirements

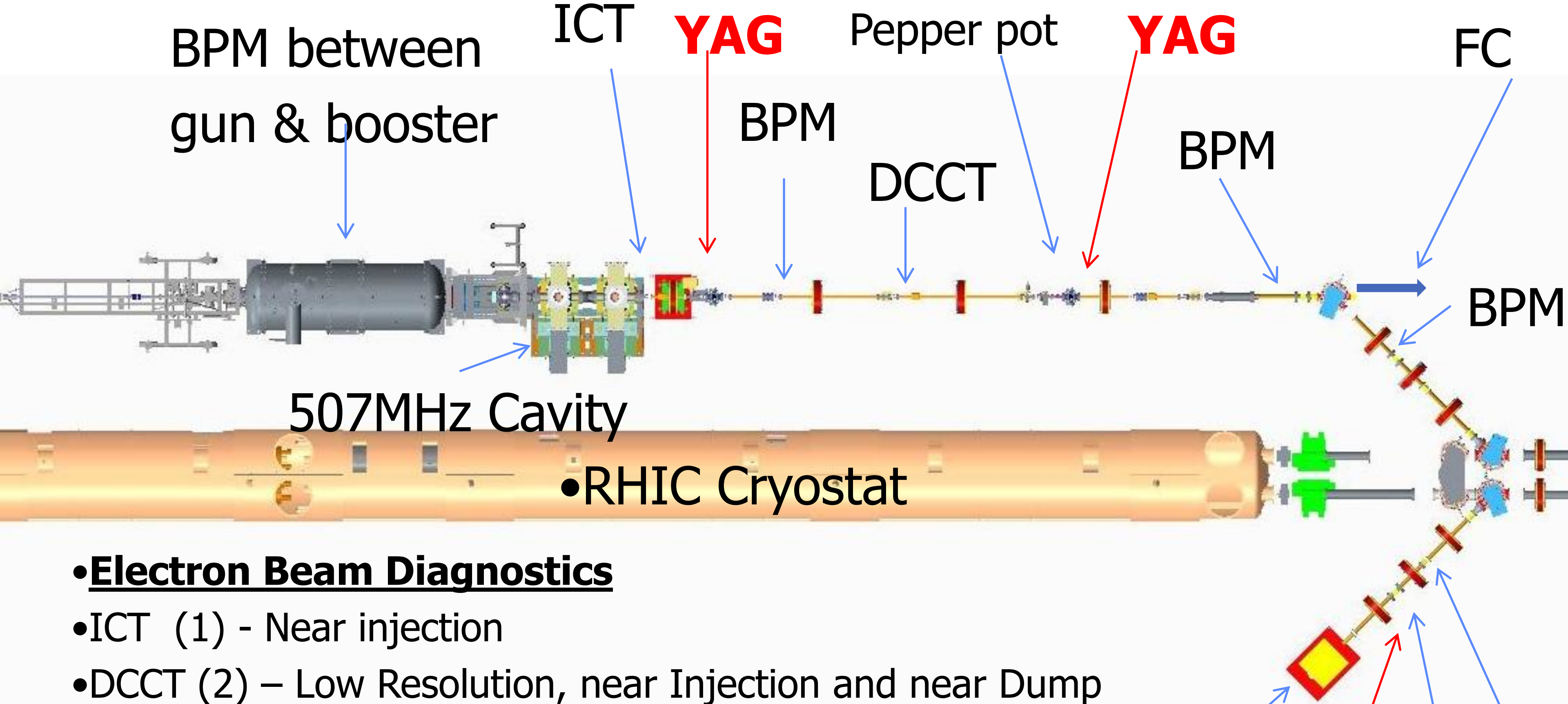
- **Phase-lock of SRF and ion revolution frequency** $$\frac{f_{SRF}}{f_{rev}} = h$$

- **Arrival time jitter of electron bunches < 100 ps**

- **Electron peak current jitter < 7%**

Controls systems should be similar to ERL and CEC and will be built on gained experience.

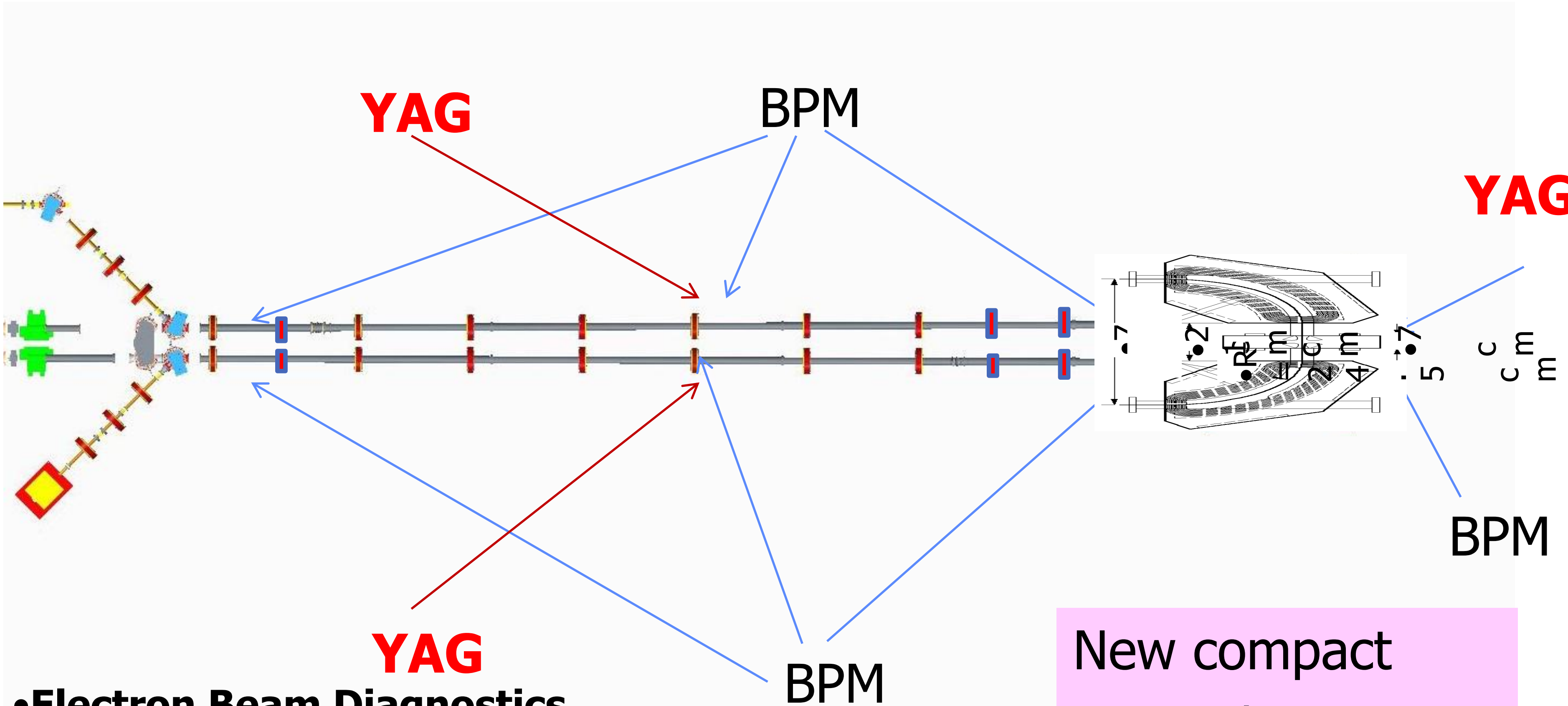
•<u>LEReC injection and Dump Instrument Layout</u>



•<u>Electron Beam Diagnostics</u>

- •ICT (1) - Near injection
- •DCCT (2) – Low Resolution, near Injection and near Dump
- •Profile Monitors (**YAG**) - (3)
- •BPMs – along beam lines (4)
- •Dump Beam Loss detectors similar to ERL Dump
- •Ion Clearing Electrodes (use BPMs if needed ?)

LEReC Cooling Section & U-Turn



New compact U-turn between RHIC beam pipes.

- **Electron Beam Diagnostics**
- Profile Monitors (**YAG**) - (3) – Plunging YAG screens
- BPMs – (7)
- Corrector locations – at every solenoid,
- For sector 1: L=18m with 9 solenoids every 2 m.

SRF accelerator parameters

Beam			
Lorentz factor	4.1	10.7	10.7
RHIC RF frequency	4.55 MHz	4.67 MHz	28.03 MHz
Electron beam kinetic energy	1.58 MeV	4.96 MeV	4.96 MeV
SRF gun and booster			
SRF frequency	84.48 MHz	84.47 MHz	84.47 MHz
Gun voltage	1.65 MV	2.58 MV	2.58 MV
E_{pk}	25.7 MV/m	40.3 MV/m	40.3 MV/m
B_{pk}	52.5 mT	82.2 mT	82.2 mT
R/Q	122.7 Ohm	122.7 Ohm	122.7 Ohm
Geometry factor	34.7 Ohm	34.7 Ohm	34.7 Ohm
Cavity Q factor at 4.5 K	2.7e9	2.7e9	2.7e9
Gun RF power	30.7 kW	84.9 kW	92.5 kW
Frequency tuning range	78 kHz	78 kHz	78 kHz
Booster voltage	0	2.58 MV	2.58 MV
Booster RF power	0	84.9 kW	92.5 kW

Electron beam parameters

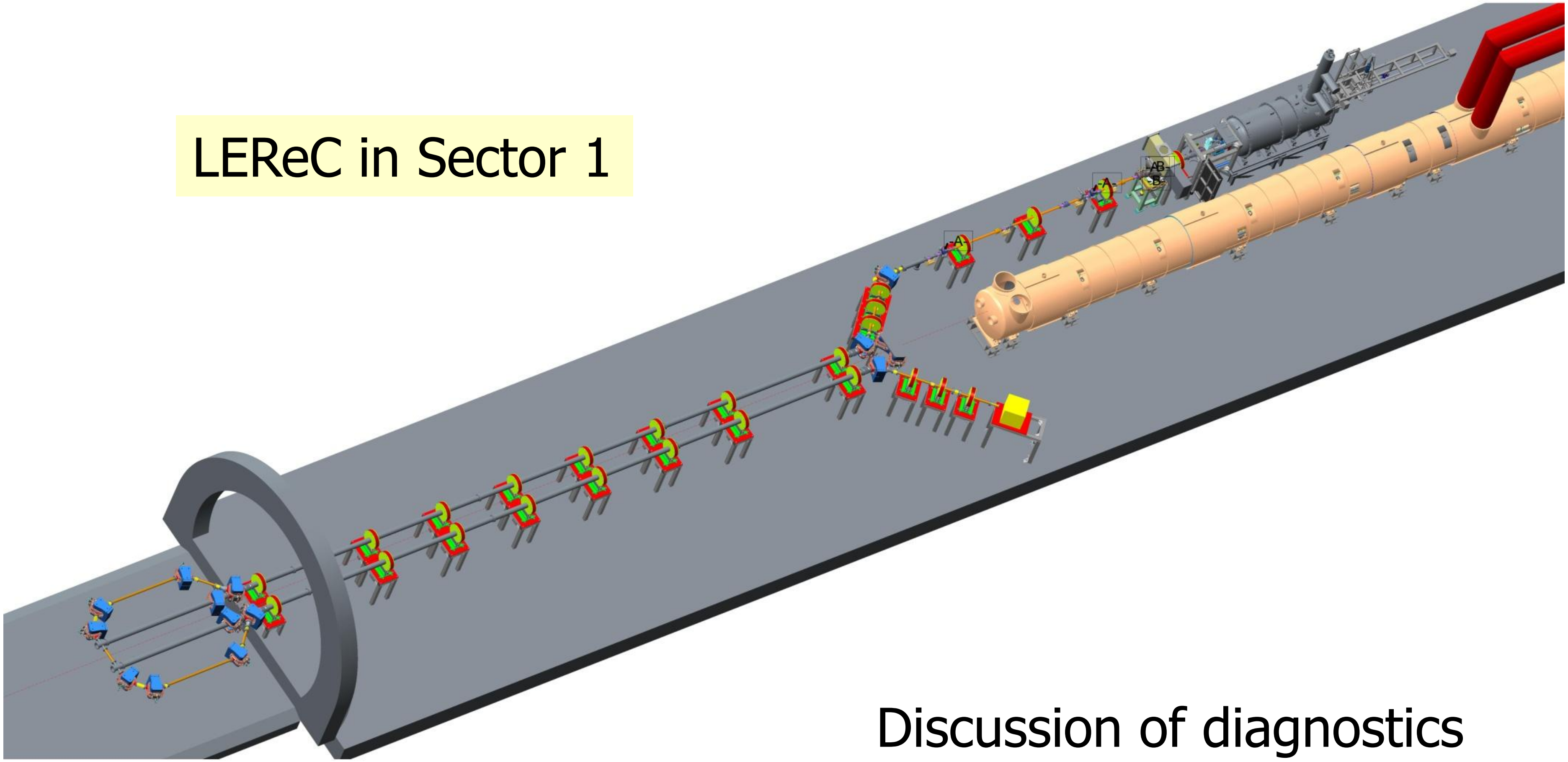
Beam			
Lorentz factor	4.1	10.7	10.7
RHIC RF frequency	4.55 MHz	4.67 MHz	28.03 MHz
Electron beam kinetic energy	1.58 MeV	4.96 MeV	4.96 MeV
Total charge per bunch train	4 (9 bunches)	7 (5 bunches)	4 (2 bunches)
$\Delta p/p$, rms	5e-4	5e-4	5e-4
Normalized rms emittance	2.5 mm·mrad	2.5 mm·mrad	2.5 mm·mrad
Transverse rms beam size	4.3 mm	2.6 mm	2.6 mm
Full bunch duration	0.5 to 1 ns	0.5 to 1 ns	0.5 to 1 ns
Electron beam current	18.2 mA	32.7 mA	35.8 mA
Beam power	28.8 kW	162 kW	178 kW

Recent proposed changes

- LEReC location: changed to Sector 1
- Electron beam injected at 40m from IP
- Cooling section: 42-61m from IP
- Matching to U-turn: 61-63.4m
- 63.4m – compact U-turn
- Some diagnostics has to be moved to accommodate new cooling section in Sector 1:

For example, IPM's and ARTUS kicker

LEReC in Sector 1



Discussion of diagnostics relocation is underway

LEReC timeline

FY2013 Physics approach/accelerator design approved – August 13-14, 2013 review.

FY2013 Design Safety Questionnaire (NEPA) and Davis-Bacon reviews - completed.

FY2013 Preliminary LEReC layout and lattice -completed.

FY2013 SCRF Cavities physics design and performance specifications - completed.

FY2014 Engineering “kick-off” meeting/assignments – October 4, 2013.

FY2014 DOE review (cost, schedule, risks) and approval: January 27-30 2014

FY2014 Engineering systems PDR, systems specifications, building requirements/system loads.

FY2014 Order SCRF Cavities/cryostat, SC solenoid, RF amplifiers, energy correction system.

FY2015 Detailed design – long lead procurements.

FY2015 Support building modification design/contracts (2015 shutdown modifications)

FY2015 Move RHIC beamline components (2015 or 2016 shutdown modifications)

FY2016 Receive and test LEReC beamline and cryogenic components

FY2016 Shutdown installation LEReC beamline and cryogenic components

FY2017 Engineering commissioning for LEReC beamline and cryogenic components

FY2017 Final installation and commissioning of SRF accelerator with beam.

FY2018 Cooling commissioning and operations (Run-18)